Accelerating innovative water treatment in Latin America

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Standfirst

Addressing sustainably the water needs of populations in countries lacking adequate infrastructure is challenging. We discuss the potential of decentralized water and wastewater treatment using electrified processes across Latin American countries, and reflect on what would help their implementation in the region.

Access to clean water and sanitation are human rights recognized by the United Nations (UN). Although an essential basic need, over 26% of the global population lack access to safely managed drinking water and more than 46% lack safely managed sanitation. This unfortunate panorama of water access inequity jeopardizes the realization of other basic human rights, such as right to an adequate standard of living and to the highest attainable standards of physical and mental well-being, that go beyond the water-food-energy nexus[1]. Conventional water treatment systems rely on centralized water treatment plants that ensure water quality standards before distributing the treated water via dedicated distribution networks[2]. Such traditional approach relies on a costly investment in infrastructure that includes long term maintenance of a grid or distribution system. However, such infrastructure may not be in place in many locations[3]. Furthermore, centralized treatment leaves unprotected all those who access water through private wells. In Latin America, where we focus attention, water scarcity and quality are growing concerns. Estimates show that more than 77 million people have no access to water for basic needs[4]. Extensive implementation of water reuse strategies can alleviate and mitigate most of the undesired social and economic consequences of water scarcity. In addition, alternative water management strategies are emerging to enable safe water access off the grid[5]. This is the case of modular/mobile, adaptive, decentralized/distributed (MAD) water systems – the idea of water systems that can be operated virtually anywhere and can be powered by renewable energy sources.

The idea of MAD systems is either to treat the water exactly where it is going to be used in the household, by developing point-of-use (POU) systems, or treat the water entering the household premise (or even an entire complex of apartments) through point-of-entry (POE) systems[6].Fig. 1 illustrates how MAD systems can either purify water from the grid or from off-grid sources (i.e., wells). These systems can be very versatile and able to adapt to the different household's characteristics defined by income level and existing infrastructure. A key element of MAD systems, as shown in Fig. 1, is their capacity to enable water reuse strategies. It is well known that toilet flushing represents 20% of the water usage in households. A MAD system can allow treating such greywater so that it can be reused for either toilet flushing or even irrigation. These water reuse practices may benefit water stressed communities by reducing the water footprint. Electrified water treatment technologies represent a transformative solution for MAD systems.

Electrochemically-driven water treatment allow to target selectively different pollutants just by carefully selecting the electrode material[7]. These technologies are intrinsically heterogeneous processes that take place at or are mediated by the electrodes. Therefore, electrochemical reactor designs are compact in nature in order to maximize the ratio of electrode area per volume of water treated. Details on the unique aspects of different electrochemical technologies can be found in the literature [8,9]. The modularity aspect allows the selection of different processes that can be combined in consecutive compact cells. Depending on the targeted pollutant, the engineering selection criteria allow defining: (i) the combination of processes to be used, (ii) the current densities to be implemented while being consistent with the current efficiencies that optimize each electrochemical process, and (iii) the verification of the degradation levels that must be met.

Myths about electrified treatment

The first uneducated myth regarding electrochemically-driven water treatment processes is the risk of electrocution. Electrochemical technologies consist of smart and compact systems where the use of electricity is just the vehicle to enable charge transfer and use of electrons as main reagent. Confined electrochemical modules do not pose a safety risk to the final user and the released effluents are not electrified. Portable lithium batteries that power-up smartphones are an example of electrochemical devices used by people daily with no associated perception of risk.

The second myth is the assumption of high costs due to the use of electrical currents to operate the water treatment system. In reality, electrochemical technologies can be operated in most instances with energy provided by a single solar panel (e.g., less than 1.0 kWh day^{-1}), which can draw the electrical cost down to zero while enabling decentralized treatment even off the electrical grid[10].

Interestingly, other commercial technologies such as reverse osmosis also require electricity to operate (i.e., feed of high-pressure pumps with energy consumptions ca. 0.09 kW h m^{-3} for 50% water recovery but depending on salinity and size of units)[11] but the general public tends to overlook that. Considering that many Latin American countries are in the tropics and therefore have excellent quality solar resources, the installation of rooftop solar could be a viable option to reduce the cost. It should be also noted that it is possible to power electrochemical water treatment through other renewable energy sources such as wind energy. Techno-economic analyses suggest that electrochemical technologies can compete with conventional POU solutions such as adsorption. For example, electrochemical oxidation technologies may have considerably lower costs than carbon block adsorption units, where the electrical cost associated to cell operation is not the driving factor [12]. It should be also noted that while adsorption processes retain the pollutants in solid matrices that after saturation generate a new residue contaminated with the same pollutants that were removed from the water, electrochemical processes can completely mineralize organic pollutants and do not generate a secondary waste or concentrated brine.

The last myth is the high material costs and their amortization. Cutting-edge electrocatalytic materials are being developed and explored at lab scale. For instance, boron-doped diamond (BDD) is deemed as the gold standard electrode for electrochemical advanced oxidation processes (EAOP)[13]. Current estimates suggest the cost is ~28 US$ cm^{-2} for BDD electrode[12]. However, these estimates consider the actual prices of the material mostly used for research purposes, in absence of a real market. If adopted to scale, it is reasonable to expect that the price will drop thanks to 'Economies of Scale' and 'Learning curves'[14]. For instance, between 1977 and 1999, the cost of rooftop solar panels decreased over 10-fold because over thousands of solar panels were installed [15]. In this vein, research efforts are focusing on the discovery and design of electrocatalysts with competitive performance and lower material and manufacturing costs. We think that it is reasonable to expect a reduction in capital costs within 10 years that will make electrochemical technologies competitive in emerging markets including across Latin America.

Competing *at larger scale*

Engineering research is highlighting electrochemical technologies at the forefront of future decentralized water treatment systems. During the last decade, many Latin American research groups have been leading the development of fundamental understanding of the water treatment of organic and inorganic pollutants along with demonstrating its competitiveness. Thereby, one would expect the surge of entrepreneur companies to commercialize these technologies. Fig. 2 maps the global spur of startup companies and shows they are largely inexistent across Latin American countries [16,17].

We feel that Latin American countries should not miss the opportunity to lead and compete not only in national markets but also at international level. It is estimated that the POU water treatment systems market in the US alone will be worth US$32.7 billion by 2023, and similar forecasts exist for other countries worldwide. Startups are critical to introduce technologies to the market, especially because they are often responsible for the development of innovations that lead to economic growth [18]. We believe that the creation of new startups will be an important step toward the effective development of electrified water technologies in Latin America. These audacious goals can be only achieved with investment in high-quality research that can bridge the gap between academia and industry. Only the institutional push from Governmental Agencies will enable the competitive creation of a technology hub. Funding initiatives in many countries are enhancing technology translation by supporting engineering entrepreneurs. For example, the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs in the US are resulting in the prolific creation of opportunities and economic growth. The idea behind such highly competitive programs is to enable domestic small businesses to engage in Federal Research/Research and Development (R/R&D) with the potential for commercialization. Some Latin American countries are supporting similar initiatives by engaging industry with academia. For example, the PIPE and

PITE programs of the São Paulo Research Foundation (FAPESP) from Brazil finances R&D projects for small and medium companies with an interest in the development of technological products or processes [19], the program START-UP CHILE funded through the Chilean Corporación de Fomento de la Producción (CORFO), CTAgua in Uruguay,[20] or RUTAN in Medellin (Colombia) created by the mayor's office of the city. These efforts in Latin America to bring industry and academia together act as incubators of emerging companies that translate technologies to higher technology readiness level and accelerate emerging technologies translation to competitive markets. Enacting more initiatives like these ones will be a key step to catalyze the development of national startups leading to innovative technological solutions, and their commercialization, by combining technical expertise with a direct understanding of local conditions and needs.

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Figure Captions

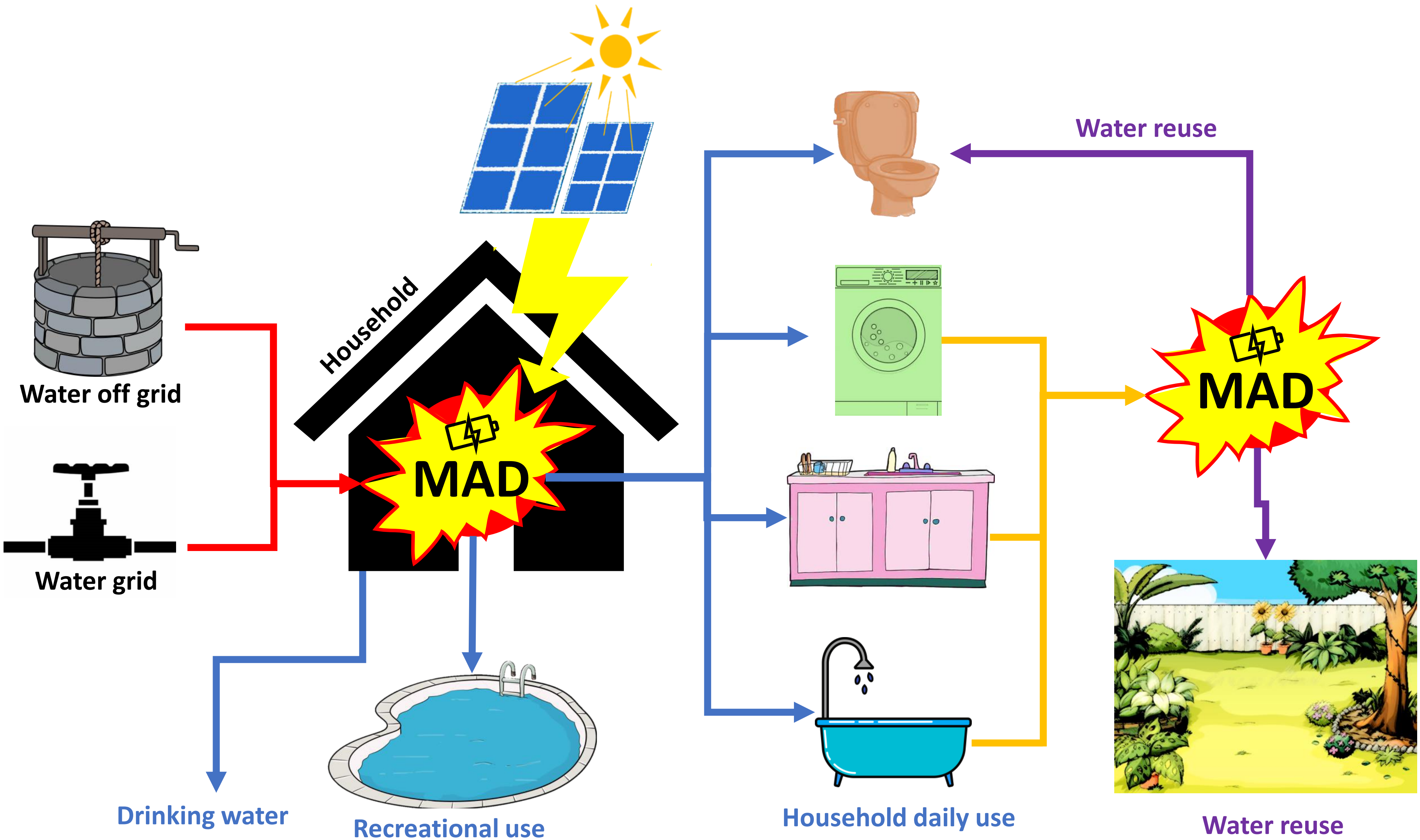
Figure 1. *Implementation of MAD systems at household level to ensure water quality and enable water reuse practices.*

Figure 2. *Worldwide distribution of electrochemical water treatment startups. Author's calculations based on data from references 16 and 17*[16,17].

References

1. Liu, J. *et al.* Nexus approaches to global sustainable development. *Nat Sustain* **1**, 466–476 (2018).
2. Roefs, I., Meulman, B., Vreeburg, J. H. G. & Spiller, M. Centralised, decentralised or hybrid sanitation systems? Economic evaluation under urban development uncertainty and phased expansion. *Water Res* **109**, 274–286 (2017).
3. Jeon, I., Ryberg, E. C., Alvarez, P. J. J. & Kim, J.-H. Technology assessment of solar disinfection for drinking water treatment. *Nat Sustain* (2022) doi:10.1038/s41893-022-00915-7.
4. WADE, J. S. The Future of Urban Water Services in Latin America. *Bull Lat Am Res* **31**, 207–221 (2012).
5. Stephen, H. Decentralized Water and Wastewater Treatment. in *Planet Water* 121–154 (John Wiley & Sons, Inc., 2015). doi:10.1002/9781119198765.ch8.
6. Garrido-Baserba, M. *et al.* The third route: A techno-economic evaluation of extreme water and wastewater decentralization. *Water Res* **218**, 118408 (2022).
7. Martínez-Huitle, C. A. & Brillas, E. Electrochemical Alternatives for Drinking Water Disinfection. *Angewandte Chemie International Edition* **47**, 1998–2005 (2008).
8. Panizza, M. & Cerisola, G. Direct And Mediated Anodic Oxidation of Organic Pollutants. *Chem Rev* **109**, 6541–6569 (2009).
9. Strathmann, H. Electrodialysis, a mature technology with a multitude of new applications. *Desalination* **264**, 268–288 (2010).
10. Almeida, L. C., Garcia-Segura, S., Bocchi, N. & Brillas, E. Solar photoelectro-Fenton degradation of paracetamol using a flow plant with a Pt/air-diffusion cell coupled with a compound parabolic collector: Process optimization by response surface methodology. *Appl Catal B* **103**, 21–30 (2011).
11. Qin, M. *et al.* Comparison of energy consumption in desalination by capacitive deionization and reverse osmosis. *Desalination* **455**, 100–114 (2019).
12. Stirling, R., Walker, W. S., Westerhoff, P. & Garcia-Segura, S. Techno-economic analysis to identify key innovations required for electrochemical oxidation as point-of-use treatment systems. *Electrochim Acta* **338**, 135874 (2020).
13. do Vale-Júnior, E., dos Santos, A. J., da Silva, D. R., Fajardo, A. S. & Martínez-Huitle, C. A. Electrochemical Technologies for Detecting and Degrading Benzoquinone Using Diamond Films. *ChemElectroChem* **6**, 4383–4390 (2019).
14. Elshurafa, A. M., Albardi, S. R., Bigerna, S. & Bollino, C. A. Estimating the learning curve of solar PV balance–of–system for over 20 countries: Implications and policy recommendations. *J Clean Prod* **196**, 122–134 (2018).

15. Rabaey, K., Vandekerckhove, T., de Walle, A. van & Sedlak, D. L. The third route: Using extreme decentralization to create resilient urban water systems. *Water Res* **185**, 116276 (2020).
16. Magnisali, E., Yan, Q. & Vayenas, D. v. Electrocoagulation as a revived wastewater treatment method-practical approaches: a review. *Journal of Chemical Technology & Biotechnology* **97**, 9–25 (2022).
17. Electrochemical Water Treatment Companies. https://www.environmental-expert.com/companies/keyword-electrochemical-water-treatment-1319 (2022).
18. Goldstein, A., Doblinger, C., Baker, E. & Anadón, L. D. Startups supported by ARPA-E were more innovative than others but an investment gap may remain. *Nat Energy* **5**, 741–742 (2020).
19. São Paulo research foundation. https://fapesp.br.
20. Centro Tecnológico del Agua. https://ctagua.uy/.



Water reuse
Household
MAD
MAD
Water off grid
Water grid
Drinking water
Recreational use
Household daily use
Water reuse